

InLCA: LCA Case Studies – Using LCA to Compare Alternatives

A Diagnostic Model for Green Productivity Assessment of Manufacturing Processes

Ruby Pineda-Henson^{1*} and Alvin B. Culaba²

¹Dept. of Industrial Engineering, Holy Angel University-Angeles City, Philippines

²Dept. of Mechanical Engineering, De La Salle University-Manila, Philippines

*Corresponding author (hensonrp@dateinet.net)

Abstract

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Goal, Scope and Background. Green Productivity (GP) is a new paradigm in sustainable manufacturing where resource conservation and waste minimization constitute the strategy in simultaneously enhancing environmental performance and productivity. This productivity approach to the sustainability of industries requires the adoption of clean production technology and the development of appropriate indicators and instruments to measure environmental performance in a continuous improvement strategy that focuses on the manufacturing stage of the product life cycle. The analysis may be expanded to include the entire life cycle with increasing details on impacts, improvement strategies and indicators.

Methods. The study proposes a methodology for GP assessment that integrates the essential components of life cycle assessment (LCA) and multicriteria decision analysis specifically the analytic hierarchy process (AHP). LCA provides a systematic and holistic perspective for GP analysis that spans inventory, impact and improvement assessment. The AHP is utilized as a decision framework and valuation tool for impact and improvement assessment to come up with priority weights. Indicators are derived and measured from a streamlined LCA focused on a number of parameters within the gate-to-gate analysis to demonstrate the GP concept in relation to resource utilization and waste minimization. An input-output approach using a suitable material balance in a scenario analysis provides the basis of GP performance measurement.

Results and Conclusion. The diagnostic model is applied on a semiconductor assembly/packaging operation. From the streamlined life cycle inventory, impact factors were derived for water resource depletion (WRD), energy resource depletion (ERD), human toxicity-air (HTA), human toxicity-land (HTL), human toxicity-water (HTW), aquatic ecotoxicity (ETA) and terrestrial ecotoxicity (ETT). Valuation of impact factors using the AHP showed the high significance of ETT, HTL, WRD and ERD. This especially reflects the impact of the industry on the solid waste problem as a result of emissions to land associated with human toxicity and ecotoxicity effects and the intensive use of water and energy resources. Using scenario analysis, the effect of implementing a process-based improvement technique on a product-specific operation was determined and the highest values in GP are for energy utilization, water utilization and terrestrial ecotoxicity.

Recommendation and Perspective. Expert system technology was explored in developing a diagnostic prototype that emulates how human experts diagnose green productivity of manufacturing processes. The aim was to investigate how such a diagnosis could be performed in an intelligent fashion that it is also easily accessible as a decision support for industries. The expert system model will provide flexibility in testing the relationships of environmental performance and productivity parameters as well as in preserving and disseminating valuable human expertise in GP program implementation. This is a continuing research effort that is building the knowledge base for GP assessment. It will include case studies over a wider range or level of detail regarding the impacts and improvement techniques and the other stages of the product life cycle.

Keywords: Analytic hierarchy process; diagnostic prototype; expert system; green productivity; life cycle assessment; performance indicators; semiconductor assembly/packaging

Introduction

The growing clamor for environmentally sound products and processes poses a challenge to industries that are trying to address environmental issues in addition to traditional quality and productivity concerns to achieve competitive advantage. Many concepts and strategies of manufacturing performance have evolved over time with the increased importance of environmental and resource concerns in product development, process technology, and systems management.

In this study, the term green productivity, or GP, is adopted and used for brevity to refer to the combined concept of environmental and productivity performance of manufacturing processes. Based on the experience of the Asian Productivity Organization (APO), environmental protection measures have to be linked to productivity and quality improvements to gain acceptability and to rationalize their implementation. This gave rise to the new paradigm called green productivity (GP) in which environmental protection provides the foundation for sustainable development. Furthermore, productivity enhancement serves as the framework for continuous improvement [1]. Green productivity emerged gradually from the basic aim of increasing production with the minimum utilization of raw materials and resources to the application of appropriate technologies and sound man-

agement techniques in order to produce environmentally compatible goods for enhanced productivity.

The study aims to develop a diagnostic model for green productivity assessment of manufacturing processes that can be encoded in a software to be used as an intelligent decision support. The applicability of the methodology and diagnostic software is tested on a semiconductor assembly/packaging operation. The manufacturing processes for semiconductors are characterized by the intensive use of materials and energy and high pollution potential due to chemical-intensive processes. Water consumption for cooling and deionized water production is significant while releases, in the form of wastes or emissions, are transmitted through the various media and are evident in all stages of operation. In addition, the short lifespan of semiconductor chips due to the quick turn over in technology worsens the environmental impact considering the problems of waste disposal and resultant ecological effects. There are many opportunities for improving resource utilization and waste minimization in the semiconductor industry making the case study appropriate to demonstrate the green productivity concept.

1 Life Cycle Assessment

The life cycle or 'cradle-to-grave' concept now dominates many approaches in assessing and improving environmental performance of products and processes like design for environment, cleaner production and total quality environmental management. Life cycle assessment (LCA) as embodied in ISO 14040 is defined as a technique for assessing the environmental aspects and potential impacts associated with a product throughout its life cycle (i.e., cradle-to-grave) from raw materials acquisition through production, use, and disposal [2]. LCA is implemented as a system analysis of industry where the system begins with all the raw materials taken from the environment and ends with the outputs released to the environment [3]. In this study, the phased approach that includes inventory analysis, impact assessment and improvement assessment following the Society of Environmental Toxicology and Chemistry (SETAC) definition of LCA [4] provides the technical framework for the GP model. This study also addresses methodological issues in LCA such as valuation, streamlining, data quality, and benchmarkability.

2 Multi-Criteria Decision Analysis

The consideration of both quantitative and qualitative issues in environmental decision making as integral to GP analysis limits the use of mathematical models. The complex decision-making process combines decision theory and systems analysis, the merger of which is decision analysis [5]. Decision theory provides the logical and rational approach to decision making while systems analysis provides the methodology for systems representation and modeling necessary in analyzing complex problems.

The application of multi-criteria decision analysis (MCDA) to life cycle analysis has been documented in a number of papers indicating a wide range of selection of existing methods. The characteristic features of MCDA methods which were found preferable for LCA are the hierarchical representation of ob-

jectives, attributes, or alternatives; normalization and weighting in the context of the panel method; and aggregation of results to transform attribute values to weighting factors that determine ordinal preference or priorities [6].

The analytic hierarchy process (AHP) developed by Saaty is a method for multi-criteria decision-making and modeling that decomposes a complex decision problem into a hierarchy [7]. AHP is cited in many studies as among the decision frameworks for LCA with potential applications in life cycle impact assessment (LCIA) [8,9] and in environmental decision making [10]. The AHP decision analysis framework, consistent with the LCA concept, is used to hierarchically structure the environmental factors into impacts and improvement options. AHP as a decision support tool provides a mechanism for consistency check on qualitative judgments and a means of expressing the judgments quantitatively. AHP can measure the consistency and reduce the effect of subjectivity in the decision making process.

3 Methods

3.1 Integration of LCA and AHP

The complex analysis of green productivity performance combines two methodological approaches: LCA and AHP. It includes the determination of GP indicators and measures to validate the results of the LCA study and AHP procedure. LCA serves as the technical framework on which the decision making process is based, particularly in coming up with the decision factors i.e., impacts and improvement options.

A streamlined LCA is undertaken limiting the number of parameters for inventory and impact assessment within a gate-to-gate analysis. A predetermined set of impact parameters is established based on environmental regulation standards and the monitoring parameters set by the company. Allocation of inventory input and output data to individual impact categories yielded the impact parameters for the semiconductor assembly/packaging case study as shown in Table 1. The impact parameters can be determined for a specific process or for the over-all manufacturing process. Considering the whole operation, the significant impact factors noted were water resource

Table 1: Model parameters for impact assessment

Impact	Indicator	Process
Water resource depletion (WRD)	DI water	Die preparation Solder plating
	Tap water	Die preparation Die attach Molding Solder plating
Energy Resource depletion (ERD)	Electricity	All processes
Human Toxicity – Air (HTA)	Pb vapor	FL assembly Die attach
Human Toxicity – Land (HTL)	Heavy metal wastes	FL assembly Solder plating
Human Toxicity – Water (HTW)	Waste water (acidic)	Solder plating
Ecotoxicity – Aquatic (ETA)	Waste organic solvent (methylene chloride)	Flux cleaning
Ecotoxicity – Terrestrial (ETT)	Mold runners	Molding

Table 2: Model parameters for improvement assessment

Improvement Technique	Description
Material-based techniques (MBT)	Raw material substitution or usage reduction of (non-renewable, hazardous, toxic) primary raw materials/ chemicals with renewable, non-hazardous or non-toxic materials.
Energy-based techniques (EBT)	Energy substitution or usage reduction by use of high efficiency equipment, improve transfer efficiency by minimizing energy losses due to poor insulation, use environment-friendly energy sources.
Process- or equipment-based techniques (PET)	Process or equipment modification for higher efficiency, reconditioning to produce less waste, in-plant recycling process, in-plant segregation techniques for reusable waste e.g. solvent extraction process integration of air, water and other pollution controls; automation.
Product-based techniques (PBT)	Improving product quality in relation to defects and end-of-life disposal aspects; product quality control and standardization; product design innovation for environmental compatibility.
Management-based techniques (MGMT)	Management strategies not included in the first 4 classification e.g., good housekeeping practices, employee training, proper inventory management to reduce waste in the production process or other functions.

depletion (WRD), energy resource depletion (ERD), human toxicity-air (HTA), human toxicity-land (HTL), human toxicity-water (HTW), aquatic ecotoxicity (ETA) and terrestrial ecotoxicity (ETT). Based on literature survey and observation of relevant company practices, the productivity improvement techniques considered were categorized into material-, energy-, process-, product- and management-based techniques as defined in Table 2. The initial classification of impact and improvement components in the model can be redefined or expanded to realistically feature dynamic conditions in the manufacturing environment.

Multi-criteria decision analysis, using AHP, provides the decision framework and the valuation tool for developing priority indices for environmental impact and improvement assessment. The AHP framework is consistent with the LCA concept in the manner of hierarchically structuring the decision elements into impacts and improvement options and providing the nec-

essary correlation as shown in Fig. 1. The top-most level represents the over-all goal, which is to improve green productivity performance. Environmental impacts and improvement options constitute the second and third levels of the hierarchy, respectively. Pair-wise comparisons of the elements are done at each level with respect to the element or elements of a higher level in the hierarchy. The impacts are compared pair-wise with reference to the goal of GP resulting in the relative weights of the impact factors (W_i). The improvement options in the third level are then compared pair-wise with respect to each of the impacts in the next second level to determine the weights of the options with respect to each impact factor (K_{ij}). From the values of W_i and K_{ij} , the weight factor A_j which represents the priority weight given to each option with respect to the overall goal of improving green productivity performance can be calculated from the following equation:

$$A_j = \sum W_i K_{ij} \quad (1)$$

$i = 1, 2, \dots, n$ impact factors

$j = 1, 2, \dots, m$ options

where

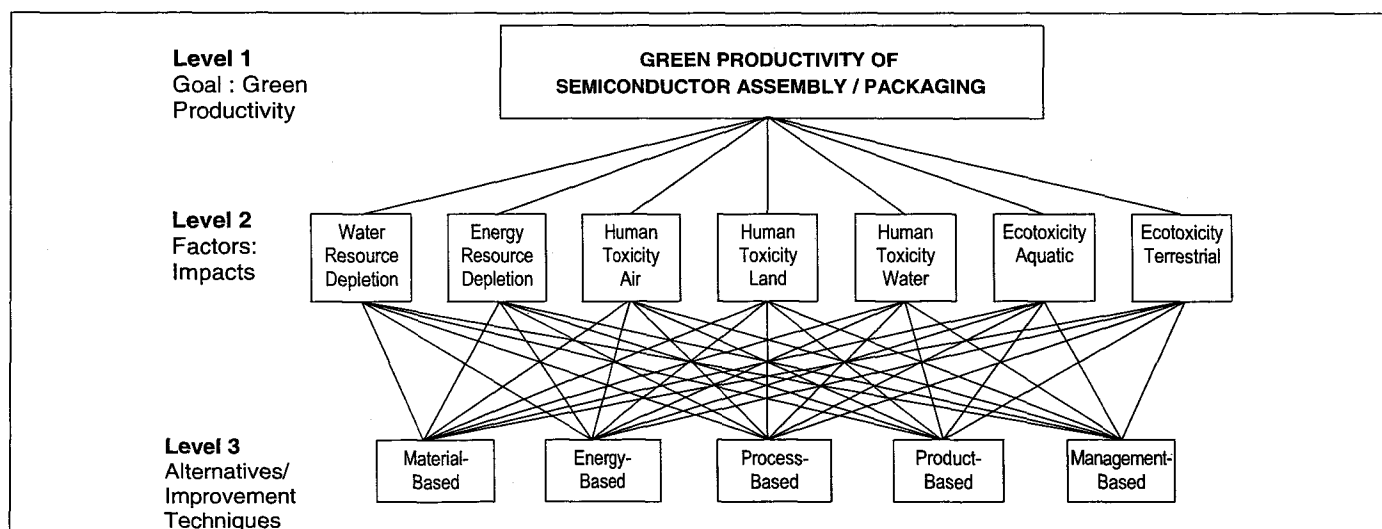
W_i = the relative weight of impact factor i with respect to the over-all goal

K_{ij} = relative weight of option j with respect to impact i

A_j = priority weight of option j

3.2 Valuation using analytic hierarchy process

In the study, human expert judgment is utilized in the impact and improvement analyses on a product-specific semiconductor assembly/packaging operation. The experts were chosen for their expertise and industry experience covering the fields of process engineering, pollution control and quality and productivity management. Each expert was briefed about the objectives of the study, the principles of LCA, and the details of the AHP methodology. Inputs solicited from the experts consisted of their judgments on the relative importance of the impact factors and the improvement strategies in the manufacturing operations.

**Fig. 1:** Decision hierarchy structure

Some features of the AHP that were found suitable for complex analysis such as the case study described in this paper are the ability to accommodate mixed data while combining quantitative and qualitative information in the analysis; the participatory nature allowing the active involvement of multiple experts, stakeholders, and decision makers; the ability to decompose complex problems into simpler units organized in a hierarchy; and the transparent analytical procedures that encourage participation in a decision making process, with the incorporation of an acceptable consistency check on the ratings given by the experts as part of the AHP procedure [11].

3.3 GP performance indicators

The study utilizes the general approach to the development of environmental performance indicators based on the classification of environmental impacts, i.e., one indicator for each type or category of impact [12]. ISO 14031 explicitly prescribes the use of performance indicators in environmental management systems to support a continuous improvement strategy [13,14]. The selection of meaningful indicators and metrics is critical in environmental performance evaluation and should be specific for each industry and tailored to the individual organization [15]. Therefore, mass-based green productivity indicators which integrated the environmental and productivity aspects were prescribed corresponding to the seven impact categories that were established. The criteria for green productivity were based essentially on maximization of resource utilization and minimization of waste. ISO 14031 describes the basis for environmental evaluation as the so-called operational system, which corresponds to an input-output analysis of material flows [14]. In the context of productivity being a ratio of output to inputs, three types of GP ratios associated with the impacts are water utilization ratio, energy utilization ratio, and waste or emission ratios.

The first set of indicators for semiconductor assembly operations which are GP water utilization ratio (GPWUR) and GP energy utilization ratio (GPEUR) are based on the resource productivity concept. The remaining five indicators which are GP human toxicity-air emission ratio (GPHAR), GP human toxicity-land waste ratio (GPHLR), GP human toxicity-water waste ratio (GPHWR), GP aquatic ecotoxicity waste ratio (GPEAR), and GP terrestrial ecotoxicity waste ratio (GPETR) are based on minimization of wastes associated with toxicity effects. The ratios may be calculated from the input-output data for each process or for the over-all operation using the formula in Table 3.

The corresponding indices are computed for a specific period or scenario where an improvement technique is implemented. By ratio and proportion, the GP index for test sce-

nario X is calculated from the GP ratios computed for the reference or baseline condition B and scenario X. Thus, for each green productivity indicator, the GP index for scenario X is determined as follows:

GP Index for Scenario X =

$$\text{GP Ratio for Scenario X} / \text{GP Ratio for Scenario B} \quad (2)$$

In the absence of industry benchmarks on green productivity, the indices are interpreted on the basis of a reference index of 1 for the baseline condition. An index greater than 1 for the performance indicators in a given scenario is interpreted as an improvement while an index less than one means decline in green productivity.

3.4 Application on semiconductor assembly and packaging

The assessment is confined to a semiconductor assembly/packaging operation, which is summarized in seven stages: die preparation, lead frame assembly, die attach, flux cleaning, molding, soldering and testing (Fig. 2). For a given production run and functional unit of 19 wafers as process input, all inputs, wastes or emissions and products are expressed in kilograms (kg) while energy is expressed in kilowatt-hr (kWh). For wastes and emissions, the outputs are established using suitable material balances. Process energy data is obtained for each unit process considering the process time and capacity rating of the equipment. All data entries and calculations for the inventory, AHP implementation of impact and improvement analyses, and determination of green productivity indicators were initially implemented in a spreadsheet program.

3.5 Developing the green productivity diagnostic expert system

The methodological procedure for green productivity assessment runs parallel to the knowledge acquisition process in the development of a diagnostic expert system. Expert knowledge and other information is acquired from a variety of sources including text analysis, structured and unstructured interviews, human expert judgment, and survey of environmental and productivity programs in various semiconductor assembly/packaging operations. The schematic chart for the green productivity assessment methodology is shown in Fig. 3. The GP model which is translated into a software code consists of a measurement subsystem and a diagnostic subsystem. The measurement subsystem employs a database program for importing data and calculations in inventory, impact, improvement and GP assessment while the diagnostic subsystem is responsible for the interpretation of inventory data, impact weights, improvement priority weights, and GP ratios and indices. The structure of the knowledge base is shown in Fig. 4.

Table 3: Green productivity indicators

Green Productivity (GP) indicators	Acronym	GP ratio determination
GP water utilization ratio	GPWUR	kg product / kg water input
GP energy utilization ratio	GPEUR	kg product / kw-hr energy input
GP human toxicity-air emission ratio	GPHAR	kg product / kg Pb vapor emission
GP human toxicity-land waste ratio	GPHLR	kg product / kg heavy metal waste
GP human toxicity-water waste ratio	GPHWR	kg product / kg acidic waste water
GP ecotoxicity-aquatic waste ratio	GPEAR	Kg product / kg organic solvent waste
GP ecotoxicity-terrestrial waste ratio	GPETR	kg product / kg mold runner waste

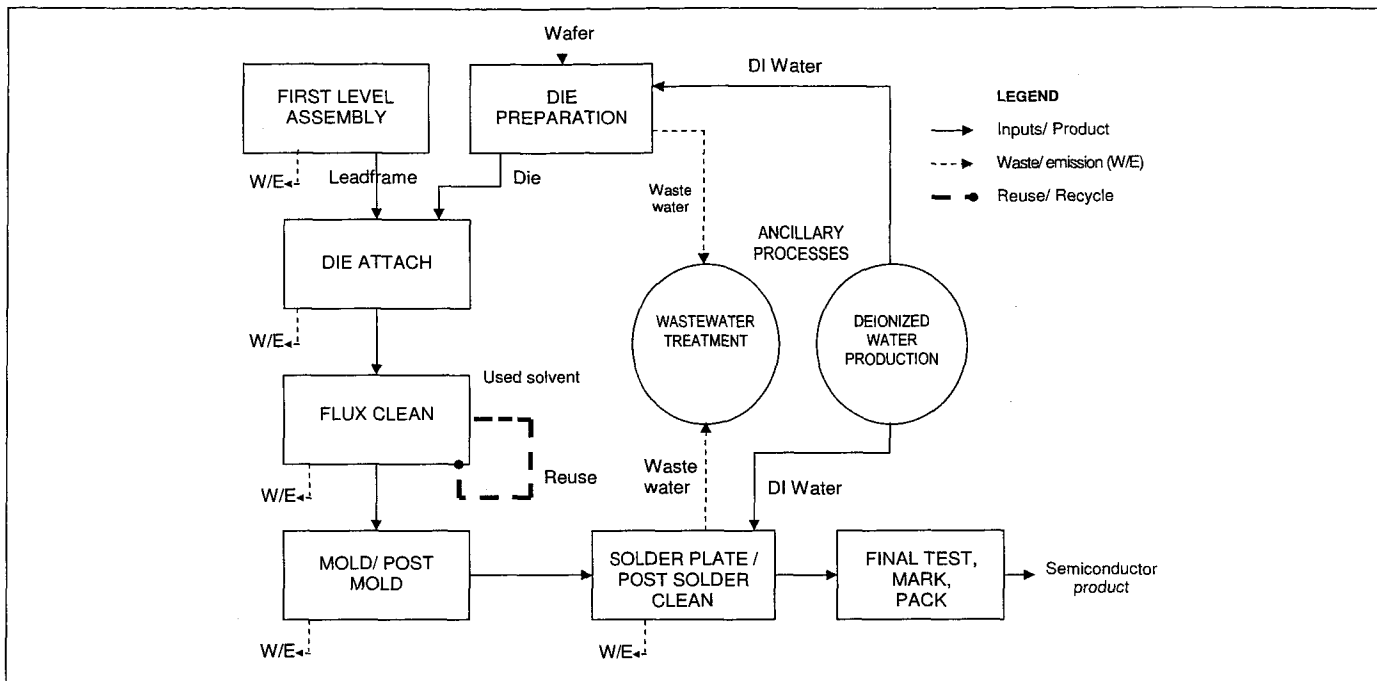


Fig. 2: Process flowchart for semiconductor assembly

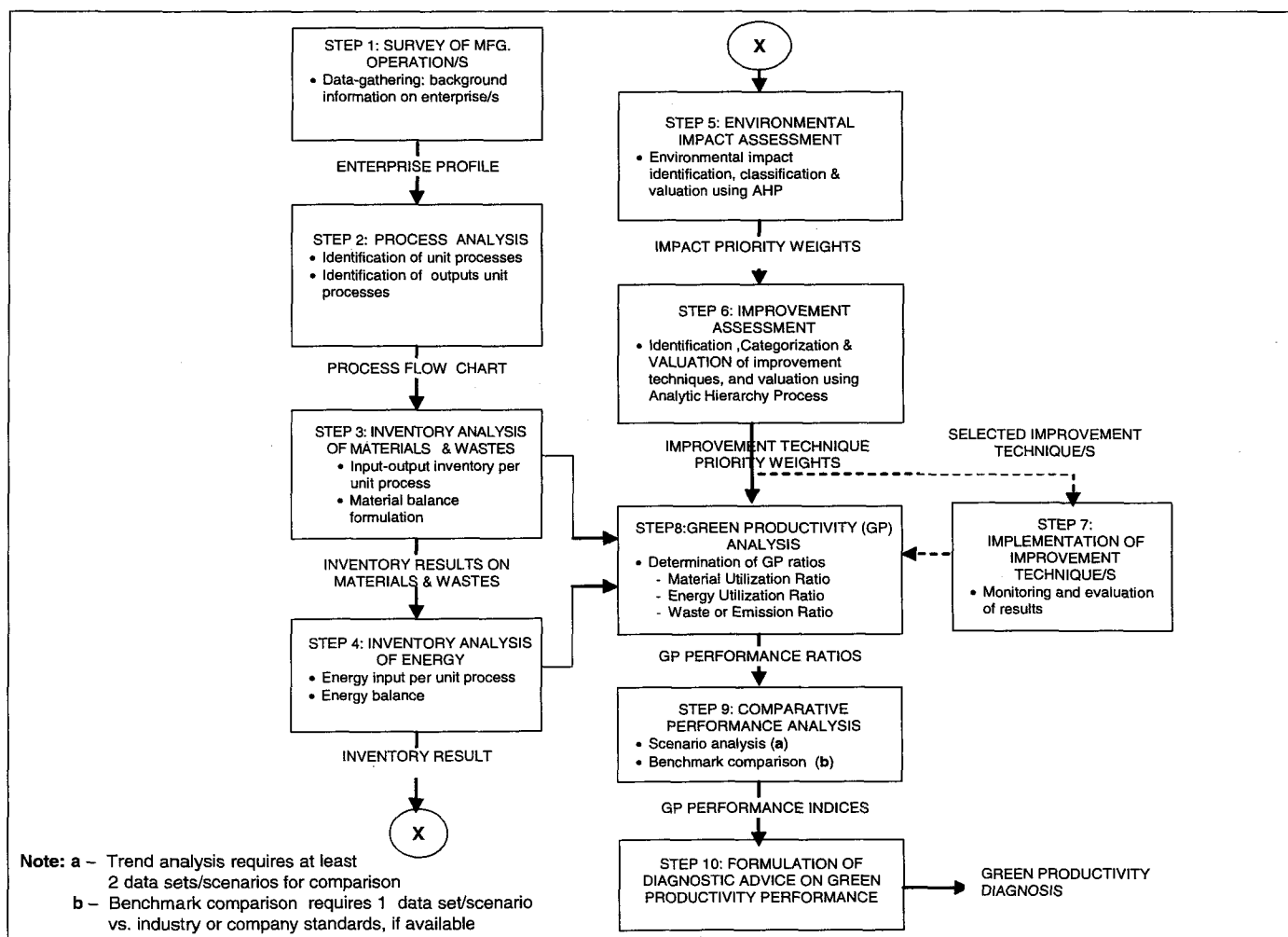


Fig. 3: Green productivity assessment methodology

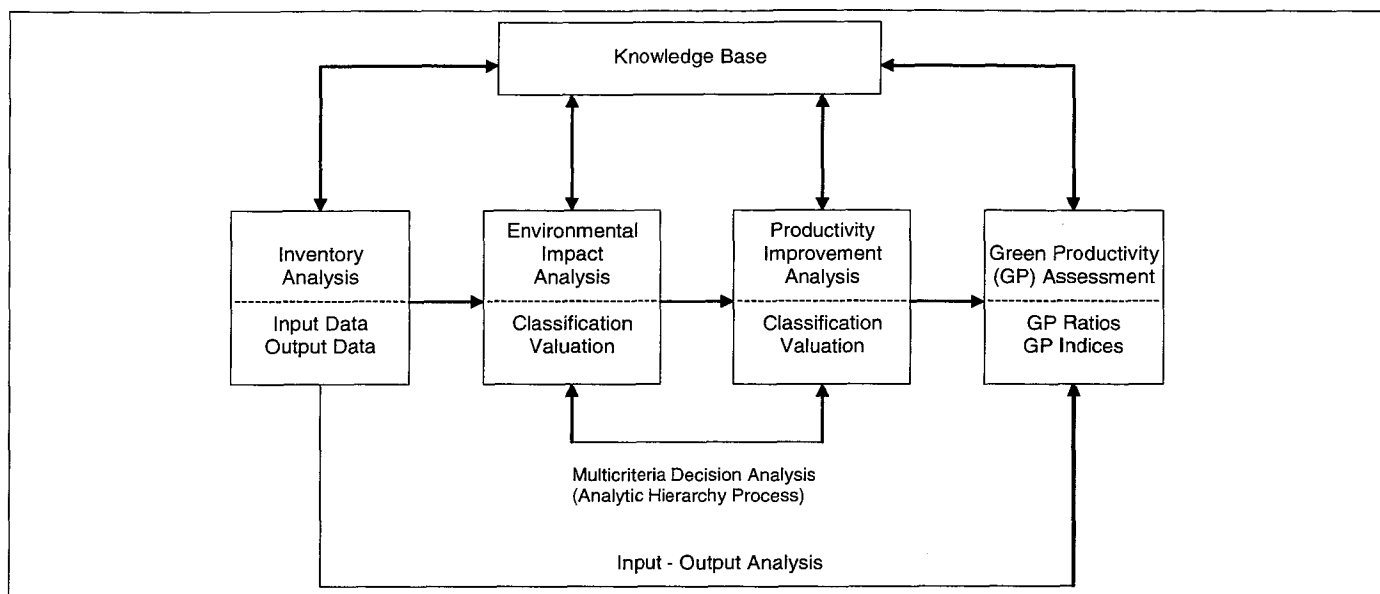


Fig. 4: Green productivity expert system structure

The design features of the prototype that were implemented by the expert system upon testing on the semiconductor assembly case study are:

- ability to assert the appropriate databases for inventory analysis, impact and improvement valuation, green productivity performance measure on ratios and indices as facts in its fact-lists;
- ability to compute performance measures for two consecutive test periods and compare the values with one as the reference condition;
- ability to develop diagnoses based on asserted facts

4 Results and Analysis

4.1 Inventory analysis

Primary data were used to the extent possible by actual measurement of material and energy inputs and outputs at designated processes and equipment. The inventory data for a baseline condition are organized in a spreadsheet program where waste and emissions are calculated using suitable material balances. The significant input data are associated with impacts on water and energy utilization while the output data are linked to impacts associated with toxicity effects of wastes and emissions segregated into process streams: air, land and water. The impacts that were identified based on inventory data are water resource depletion (WRD), energy resource depletion (ERD), human toxicity-air (HTA), human toxicity-land (HTL), human toxicity-water (HTW), aquatic ecotoxicity (ETA) and terrestrial ecotoxicity (ETT). Two sets of inventory data were needed to illustrate improvement in green productivity performance of processes and these are further discussed under scenario analysis.

4.2 Impact and improvement analyses using the AHP

For the semiconductor assembling/packaging case study, the summary of AHP priority weights for the impact factors and improvement options are presented in Table 4. Consider-

ing the aggregate results, the relative weights (W_i) of the impact factors in the order of significance are: ETT=0.21, HTL=0.15, WRD=0.14, ERD/HTA=0.13, HTW/ETA=0.12. These weights are to be interpreted as prioritization of the impacts according to their significance to the goal of improving green productivity performance. Terrestrial ecotoxicity is highly prioritized by all the experts, followed by human toxicity-land, water resource depletion, energy resource depletion which is equally prioritized with human toxicity-air and lastly, human toxicity-water which is of equal significance to aquatic ecotoxicity. This reflects the impact of the industry to the solid waste problem as a result of emissions to land associated with human toxicity and ecotoxicity effects.

The improvement options were compared and rated pairwise by the experts with reference to each of the impact factors. Considering the aggregate results, the relative weights of the improvement options (A_i) in the order of priority are: material-based technique (MBT) = 0.28, process/equipment-based technique (PET) = 0.27, energy-based technique (EBT) = 0.18, management-based technique (MGT) = 0.17 and product-based technique (PBT) = 0.12. The priority weights obtained from the improvement assessment phase indicated material-based and process/equipment-based techniques as highly prioritized with reference to the over-all goal of improving green productivity performance.

The weight given to terrestrial ecotoxicity (ETT) as the most important impact parameter for evaluating GP performance is consistent with the high priority weights obtained for material-based technique and process/equipment-based technique when evaluated relative to terrestrial ecotoxicity. The result from the AHP in the form of a set of weighting factors can be adopted by the firm as an internal control standard in prioritizing impact problems to be addressed and improvement strategies to be implemented. For the case study, a process/equipment-based improvement technique was implemented to demonstrate the green productivity concept.

Table 4: Summary valuation of impacts and improvement options using AHP

Expert A								
Impacts	WRD	ERD	HTA	HTL	HTW	ETA	ETT	
Relative weight of impacts, W_i	0.20	0.17	0.10	0.12	0.09	0.09	0.23	
Options	Relative weight of options with reference to impacts, K_{ij}							A_j
MBT	0.12	0.19	0.17	0.34	0.28	0.31	0.36	0.25
EBT	0.24	0.41	0.29	0.18	0.24	0.23	0.14	0.24
PET	0.44	0.22	0.25	0.22	0.16	0.19	0.24	0.26
PBT	0.11	0.08	0.14	0.12	0.16	0.14	0.10	0.11
MGMT	0.10	0.10	0.14	0.14	0.17	0.27	0.16	0.14
Expert B								
Impacts	WRD	ERD	HTA	HTL	HTW	ETA	ETT	
Relative weight of impacts, W_i	0.19	0.19	0.10	0.13	0.08	0.09	0.22	
Options	Relative weight of options with reference to impacts, K_{ij}							A_j
MBT	0.24	0.13	0.24	0.33	0.27	0.37	0.36	0.27
EBT	0.15	0.27	0.16	0.18	0.14	0.22	0.17	0.19
PET	0.35	0.36	0.32	0.22	0.24	0.18	0.23	0.28
PBT	0.11	0.13	0.12	0.14	0.09	0.13	0.09	0.11
MGMT	0.16	0.11	0.16	0.13	0.26	0.11	0.16	0.15
Expert C								
Impacts	WRD	ERD	HTA	HTL	HTW	ETA	ETT	
Relative weight of impacts, W_i	0.04	0.04	0.19	0.19	0.19	0.19	0.19	
Options	Relative weight of options with reference to impacts, K_{ij}							A_j
MBT	0.18	0.07	0.39	0.46	0.30	0.38	0.38	0.37
EBT	0.19	0.26	0.09	0.06	0.06	0.07	0.07	0.08
PET	0.46	0.48	0.21	0.31	0.37	0.24	0.24	0.30
PBT	0.08	0.05	0.07	0.05	0.07	0.08	0.08	0.07
MGMT	0.09	0.13	0.24	0.11	0.20	0.22	0.22	0.20
Expert D								
Impacts	WRD	ERD	HTA	HTL	HTW	ETA	ETT	
Relative weight of impacts, W_i	0.21	0.17	0.10	0.13	0.09	0.09	0.21	
Options	Relative weight of options with reference to impacts, K_{ij}							A_j
MBT	0.20	0.19	0.22	0.34	0.22	0.26	0.36	0.26
EBT	0.09	0.41	0.13	0.18	0.15	0.13	0.17	0.19
PET	0.44	0.22	0.32	0.22	0.25	0.25	0.23	0.28
PBT	0.11	0.08	0.16	0.12	0.18	0.17	0.09	0.12
MGMT	0.15	0.10	0.16	0.14	0.19	0.19	0.14	0.15
Aggregate								
Impacts	WRD	ERD	HTA	HTL	HTW	ETA	ETT	
Relative weight of impacts, W_i	0.14	0.13	0.13	0.15	0.12	0.12	0.21	
Options	Relative weight of options with reference to impacts, K_{ij}							A_j
MBT	0.19	0.15	0.24	0.42	0.26	0.31	0.34	0.28
EBT	0.17	0.32	0.16	0.15	0.15	0.16	0.14	0.18
PET	0.38	0.30	0.27	0.24	0.25	0.22	0.24	0.27
PBT	0.12	0.10	0.13	0.12	0.13	0.14	0.11	0.12
MGMT	0.14	0.13	0.19	0.14	0.21	0.17	0.18	0.17

4.3 Scenario analysis

Two sets of data are compared for the scenario analysis: the first at base-line condition and the second a test condition or scenario where a process or equipment-based technique was implemented. The programmable logic control (PLC) modification on the molding equipment reduced processing time resulting in the reduction of process energy from the

reference value of 449.49 kWh to 423.09 kWh for the molding process or from 728.46 kw-hrs to 702.06 kw-hrs for the entire operation. Likewise, water utilization in the form of cooling water, decreased from 8,262 kg to 7,704 kg in the molding process but without any significant impact in terms of contaminating the waste stream. There is improved productivity resulting from the reduction of defective products as

Table 5: GP ratios with corresponding indices and diagnosis

GP parameter	Base condition		Test scenario		GP index	Diagnostic interpretation
	Impact indicator quantity*	GP Ratio *	Impact indicator quantity*	GP ratio*		
Water utilization	15395.2000	0.002053	14837.2000	0.002131	1.038224	GP improved. Productivity based on water utilization increased.
Energy utilization	728.4626	0.043383	624.5041	0.050640	1.167285	GP improved. Productivity based on energy utilization increased.
Human Toxicity-Air (HTA) emission	0.8054	39.238595	0.8054	39.266035	1.000699	GP improved based on increase in ratio of product to HTA emission.
Human Toxicity-Land (HTL) waste	8.5575	3.693001	8.5575	3.694029	1.000278	GP improved based on increase in ratio of product to HTL waste.
Human Toxicity-Water (HTW) waste	3120.1500	0.010129	3120.1500	0.010136	1.000668	GP improved based on increase in ratio of product to HTW waste.
Ecotoxicity-Aquatic (ETA) waste	5.2800	5.985417	5.2800	5.989602	1.000699	GP improved based on increase in ratio of product to ETA waste.
Ecotoxicity-Terrestrial (ETT) waste	7.2819	4.339910	7.2819	4.345793	1.001356	GP improved based on increase in ratio of product to ETT waste.

*Impact indicator units and GP ratio formula based on Table 3

a result of the PLC modification as noted from a reference value of 31.60 kg to 31.62 kg of good products.

The GP ratios that were calculated for the baseline condition and the test scenario together with the corresponding indices and diagnosis are shown in Table 5. The results show that all the GP indices obtained have values greater than 1, indicating that the process/equipment-based technique (PLC modification) supports green productivity enhancement with reference to all seven impact parameters in the semiconductor assembly case study. Also, using the process/equipment-based technique, the highest values in GP indices are noted for energy utilization, water utilization and terrestrial ecotoxicity, in that order of significance.

5 Conclusion

The green productivity (GP) model provides an open framework that can incorporate several strategies that leverage the benefits of the various concepts of sustainable manufacturing like resource productivity, cleaner production, pollution prevention and eco-efficiency. It is an innovative way of integrating the perceptions of stakeholders, decision makers and experts on environmental and productivity issues in the design of products and manufacturing processes.

6 Recommendation and Perspective

A variety of enhancements may be made in future versions of the diagnostic prototype to include cases over a wider range or level of detail on the impacts and improvement techniques if and when sufficient databases, especially for impact analysis, become available. Impact assessment models that can be adapted or are attuned to local and regional conditions are needed to characterize impacts related to manufacturing industries. Additional knowledge from experts and decision makers can be utilized for the knowledge base as the GP program becomes widely implemented by companies. Further analysis may be extended with different objectives and options requiring expansion in the scope of the process or the product life cycle.

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